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Abraham et al.

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(54) **TUNABLE SUPERCONDUCTING NOTCH FILTER**

(71) Applicant: **International Business Machines Corporation**, Armonk, NY (US)

(72) Inventors: **David W. Abraham**, Croton, NY (US); **Jerry M. Chow**, Yorktown Heights, NY (US); **Jay M. Gambetta**, Yorktown Heights, NY (US); **Nicholas A. Masluk**, Yorktown Heights, NY (US); **Matthias Steffen**, Cortlandt Manor, NY (US)

(73) Assignee: **INTERNATIONAL BUSINESS MACHINES CORPORATION**, Armonk, NY (US)

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H01L 39/02	(2006.01)
H01L 27/00	(2006.01)
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USPC 257/30–40
See application file for complete search history.

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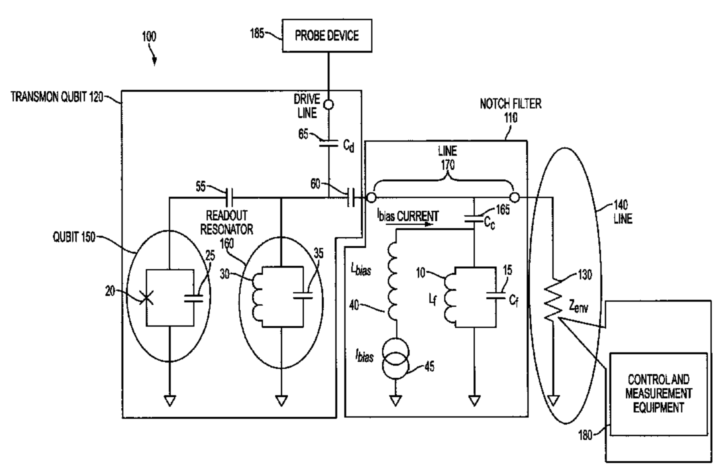
Primary Examiner — Howard Weiss
Assistant Examiner — Nelson Garces
(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP; Vazken Alexanian

(57) **ABSTRACT**

A technique relates to a superconductor tunable notch filter. A Josephson junction filter array is connected to a coupling pad and connected to ground. The Josephson junction filter array includes a filter inductance. The Josephson junction filter array connected to the coupling pad forms a filter capacitance. A Josephson junction bias array is connected to the coupling pad and connected to a current source. The Josephson junction bias array includes a bias inductance. A transmission line is connected to the coupling pad in which connection of the transmission line and the coupling pad forms a coupling capacitance, such that the filter inductance and the filter capacitance connect to the transmission line through the coupling capacitance. The Josephson junction filter array includes a notch filter frequency that is tunable according to a magnitude of a current bias from the current source.

20 Claims, 14 Drawing Sheets



(51) **Int. Cl.**
H01L 29/06 (2006.01)
H03K 17/92 (2006.01)

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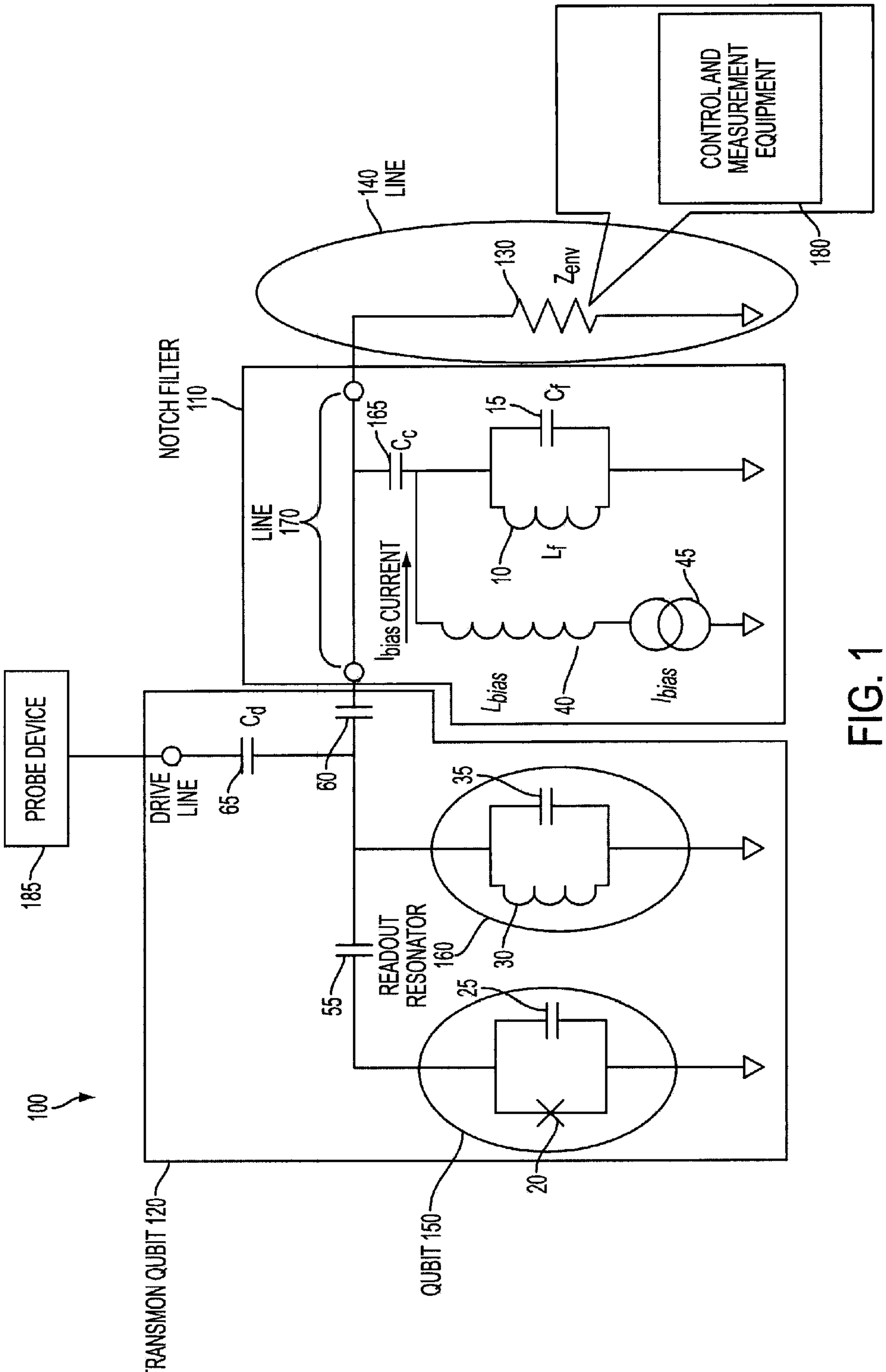

CONTROL AND MEASUREMENT EQUIPMENT
180
140 LINE
130
Z_{env}
NOTCH FILTER 110
165
C_c
15
C_f
LINE 170
I_{bias} CURRENT
10
L_f
45
L_{bias}
40
I_{bias}
PROBE DEVICE
185
DRIVE LINE
C_d
65
60
35
READOUT RESONATOR 160
30
55
25
100
20
TRANSMON QUBIT 120
QUBIT 150

FIG. 1

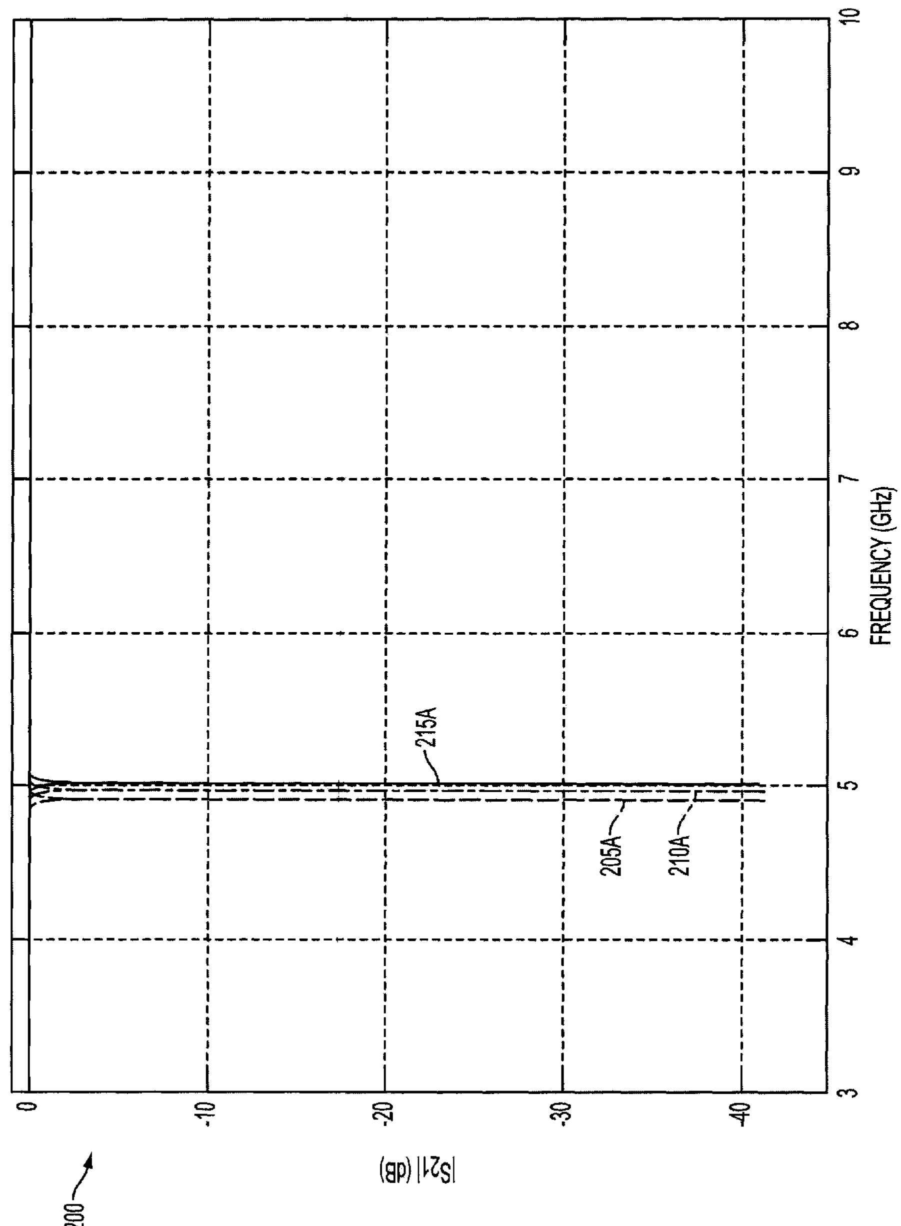

200
|S21| (dB)
0
-10
-20
-30
-40
3
4
5
6
7
8
9
10
FREQUENCY (GHz)
215A
205A
210A

FIG. 2A

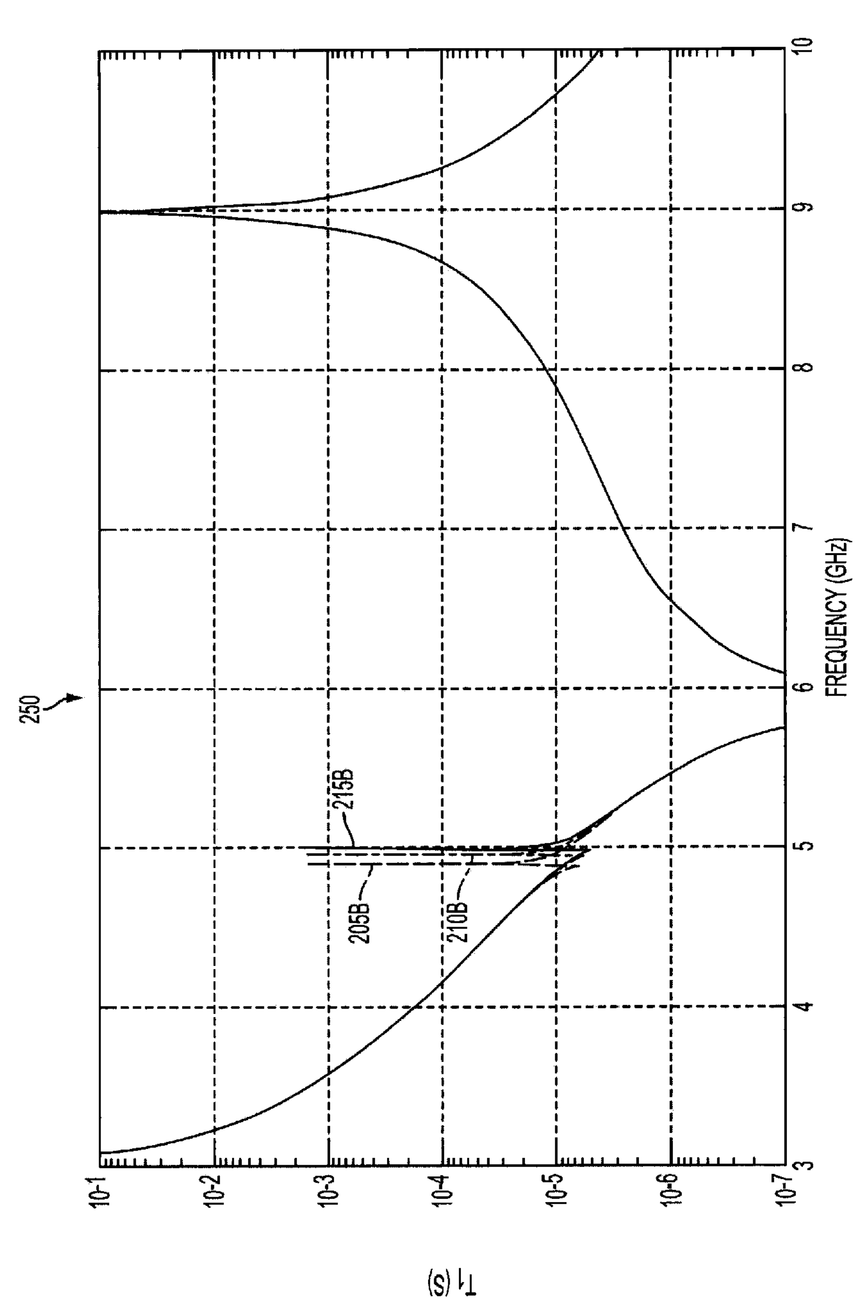

250
215B
205B
210B
FREQUENCY (GHz)
3
4
5
6
7
8
9
10
10-1
10-2
10-3
10-4
10-5
10-6
10-7
T1 (S)

FIG. 2B

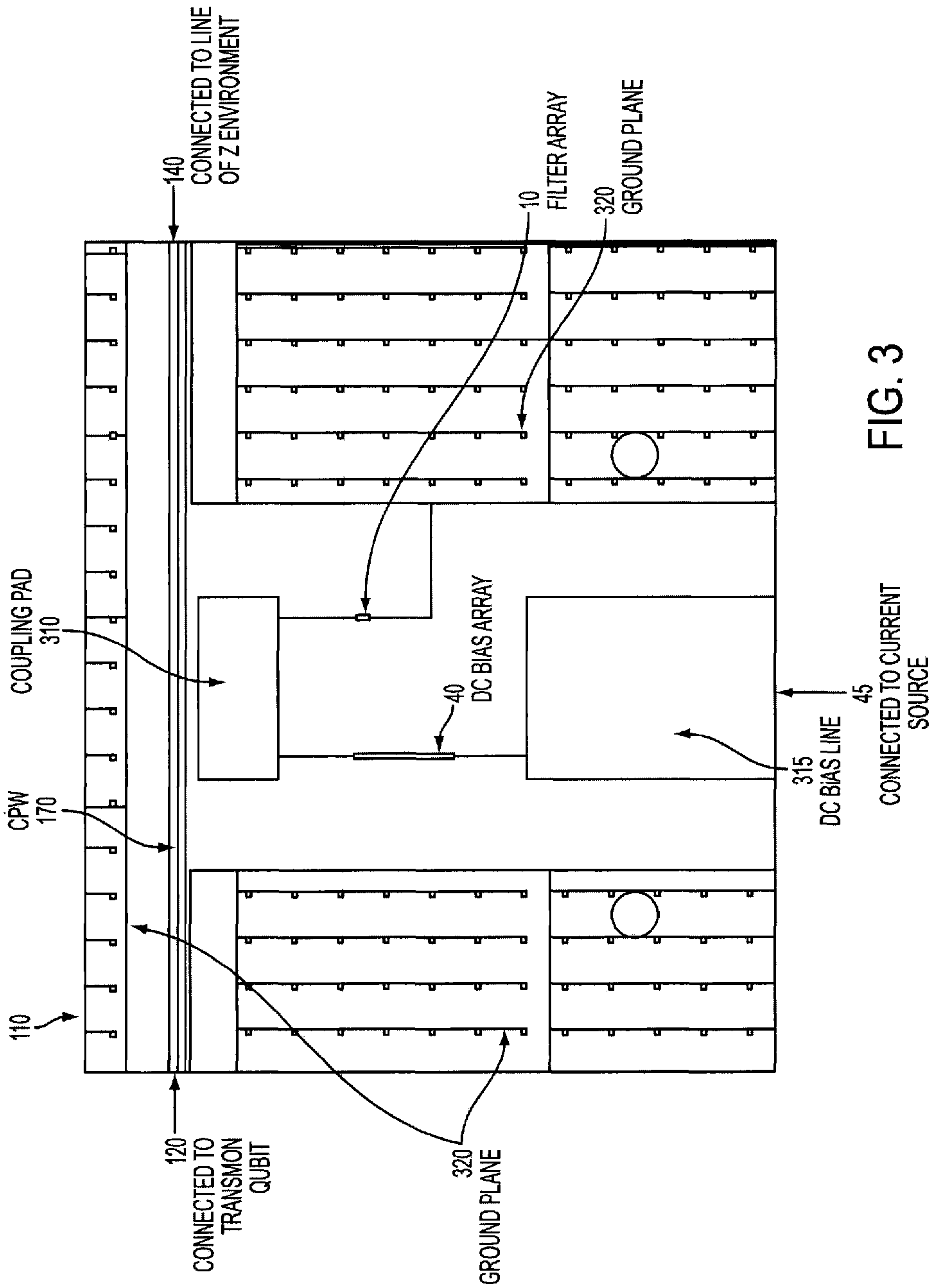

140
CONNECTED TO LINE
OF Z ENVIRONMENT
10
FILTER ARRAY
320
GROUND PLANE
COUPLING PAD
310
40
DC BIAS ARRAY
CPW
170
110
120
CONNECTED TO
TRANSMON
QUBIT
320
GROUND PLANE
315
DC BIAS LINE
45
CONNECTED TO CURRENT
SOURCE

FIG. 3

FIG. 4

400

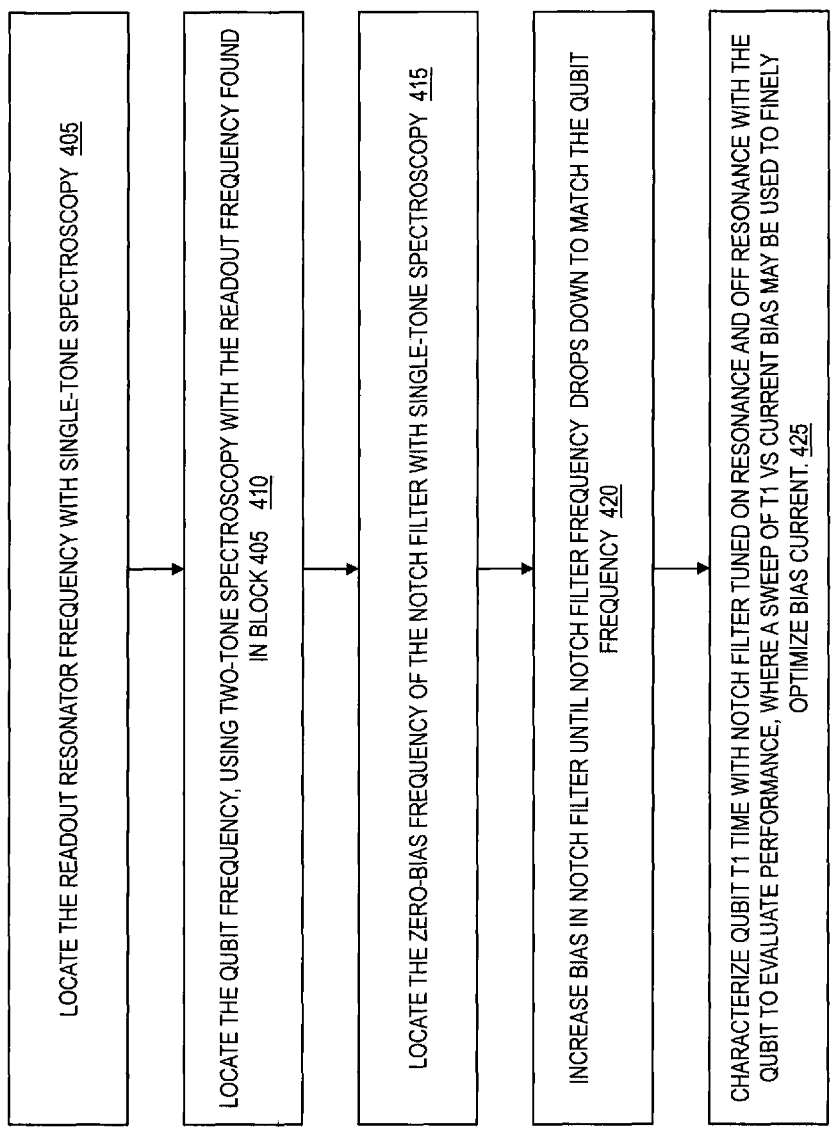
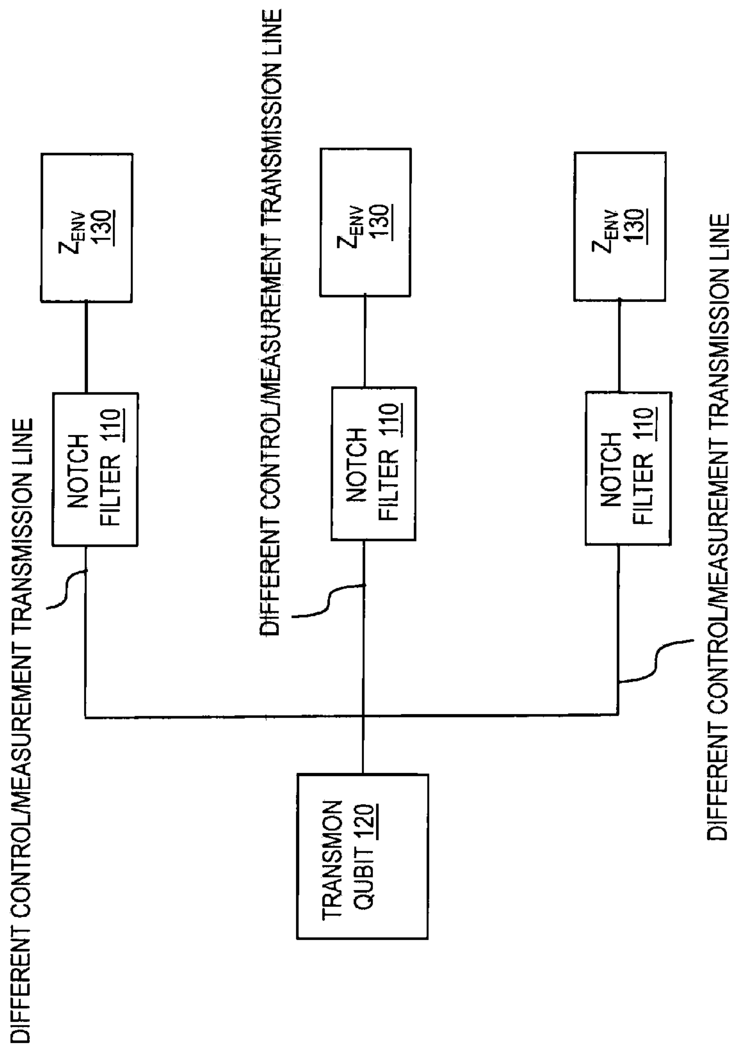

LOCATE THE READOUT RESONATOR FREQUENCY WITH SINGLE-TONE SPECTROSCOPY 405
LOCATE THE QUBIT FREQUENCY, USING TWO-TONE SPECTROSCOPY WITH THE READOUT FREQUENCY FOUND IN BLOCK 405 410
LOCATE THE ZERO-BIAS FREQUENCY OF THE NOTCH FILTER WITH SINGLE-TONE SPECTROSCOPY 415
INCREASE BIAS IN NOTCH FILTER UNTIL NOTCH FILTER FREQUENCY DROPS DOWN TO MATCH THE QUBIT FREQUENCY 420
CHARACTERIZE QUBIT T1 TIME WITH NOTCH FILTER TUNED ON RESONANCE AND OFF RESONANCE WITH THE QUBIT TO EVALUATE PERFORMANCE, WHERE A SWEEP OF T1 VS CURRENT BIAS MAY BE USED TO FINELY OPTIMIZE BIAS CURRENT. 425

FIG. 5


DIFFERENT CONTROL/MEASUREMENT TRANSMISSION LINE
DIFFERENT CONTROL/MEASUREMENT TRANSMISSION LINE
DIFFERENT CONTROL/MEASUREMENT TRANSMISSION LINE
Z_{ENV} 130
Z_{ENV} 130
Z_{ENV} 130
NOTCH FILTER 110
NOTCH FILTER 110
NOTCH FILTER 110
TRANSMON QUBIT 120

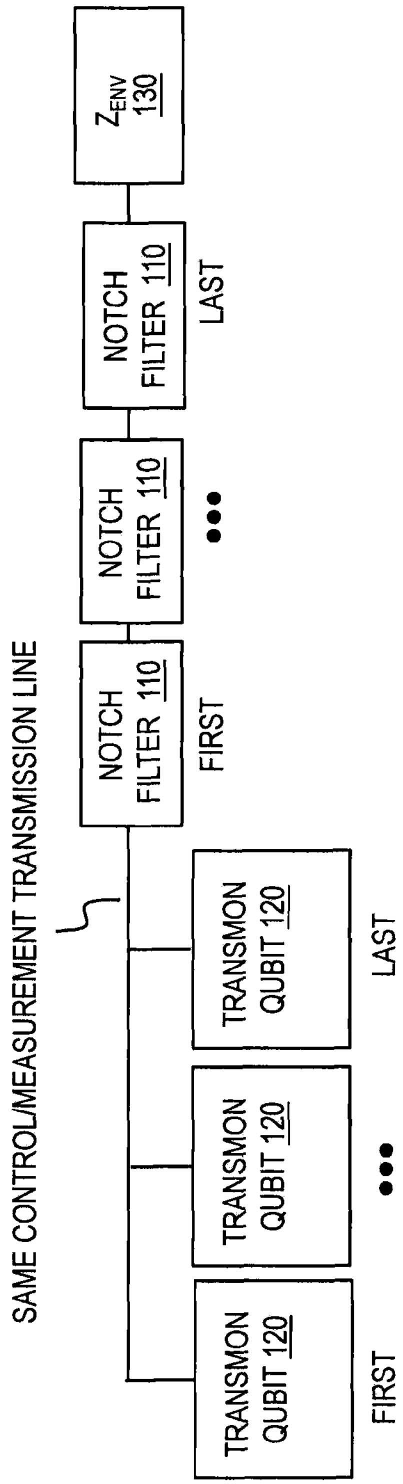

SAME CONTROL/MEASUREMENT TRANSMISSION LINE
TRANSMON QUBIT 120
FIRST
TRANSMON QUBIT 120
TRANSMON QUBIT 120
LAST
NOTCH FILTER 110
FIRST
NOTCH FILTER 110
NOTCH FILTER 110
LAST
Z_{ENV} 130

FIG. 6

FIG. 7

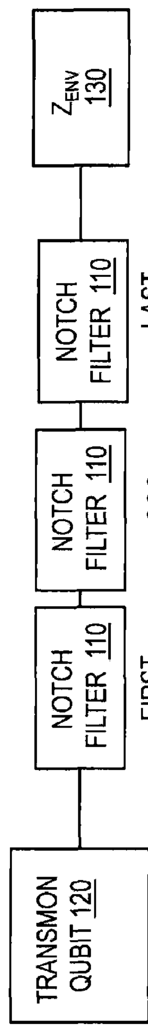

TRANSMON QUBIT 120
NOTCH FILTER 110
FIRST
NOTCH FILTER 110
NOTCH FILTER 110
LAST
Z_{ENV} 130

FIG. 8

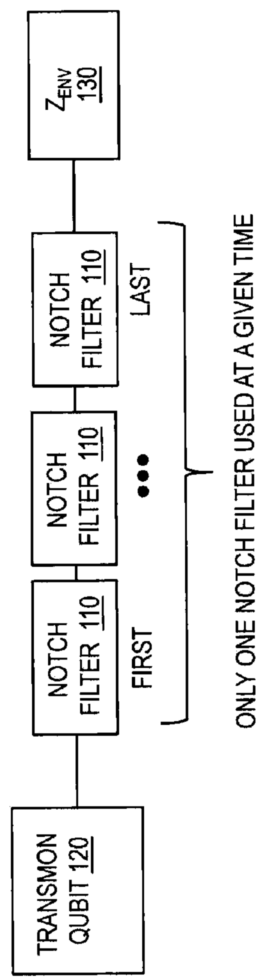

TRANSMON QUBIT 120
NOTCH FILTER 110
FIRST
NOTCH FILTER 110
NOTCH FILTER 110
LAST
Z_{ENV} 130
ONLY ONE NOTCH FILTER USED AT A GIVEN TIME

FIG. 9

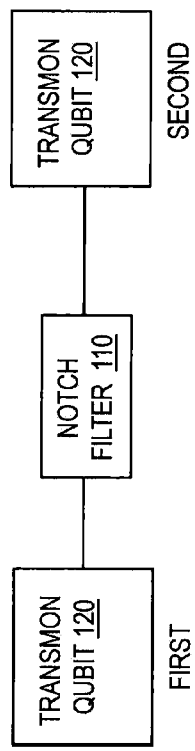
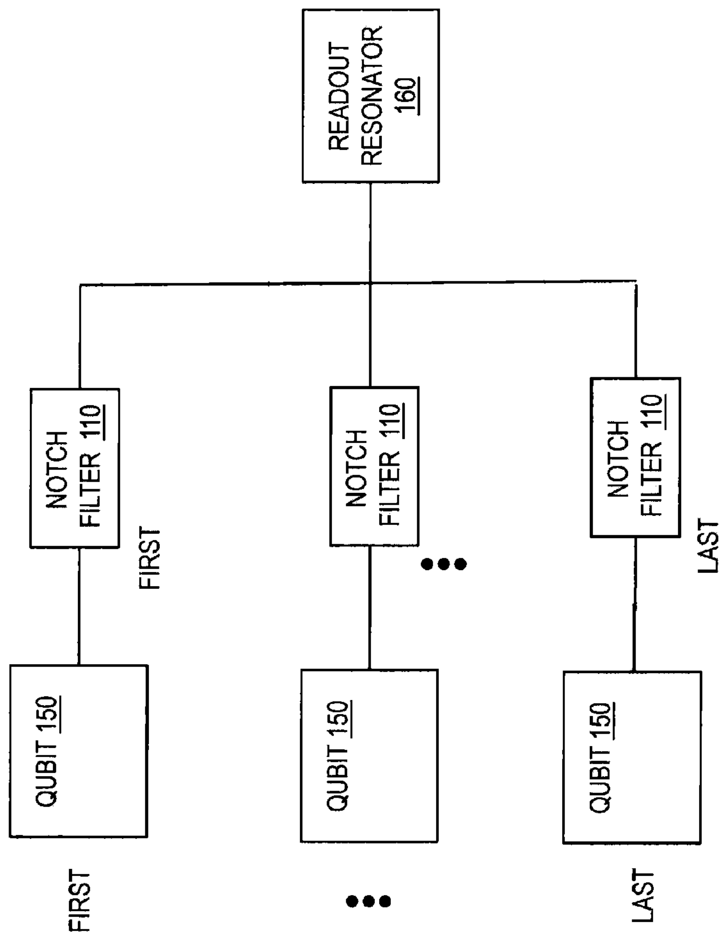

TRANSMON QUBIT 120
FIRST
NOTCH FILTER 110
TRANSMON QUBIT 120
SECOND

FIG. 10


READOUT RESONATOR 160
NOTCH FILTER 110
NOTCH FILTER 110
NOTCH FILTER 110
FIRST
LAST
QUBIT 150
QUBIT 150
QUBIT 150
FIRST
LAST

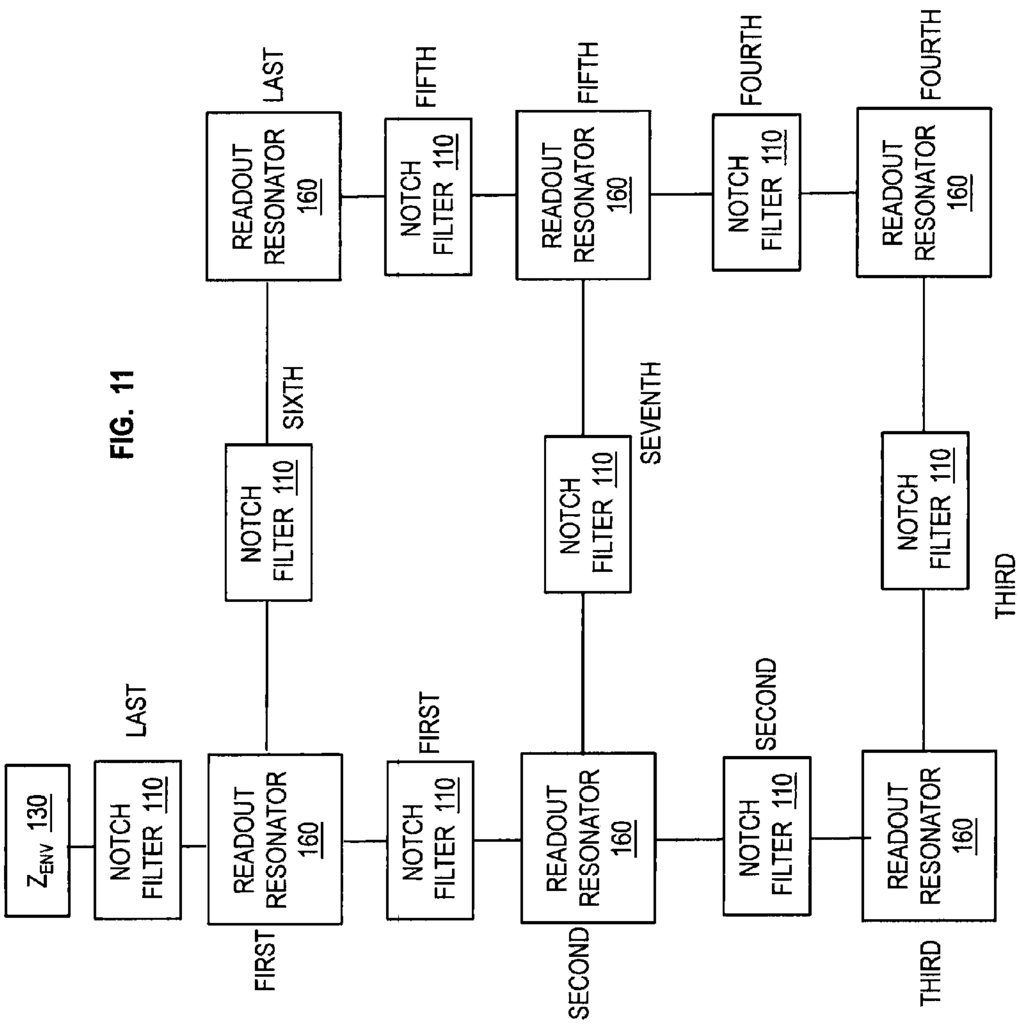

Z_ENV 130
NOTCH FILTER 110
LAST
READOUT RESONATOR 160
FIRST
NOTCH FILTER 110
FIRST
READOUT RESONATOR 160
SECOND
NOTCH FILTER 110
SECOND
READOUT RESONATOR 160
THIRD
NOTCH FILTER 110
SIXTH
NOTCH FILTER 110
SEVENTH
NOTCH FILTER 110
THIRD
READOUT RESONATOR 160
LAST
NOTCH FILTER 110
FIFTH
READOUT RESONATOR 160
FIFTH
NOTCH FILTER 110
FOURTH
READOUT RESONATOR 160
FOURTH

FIG. 11

FIG. 12

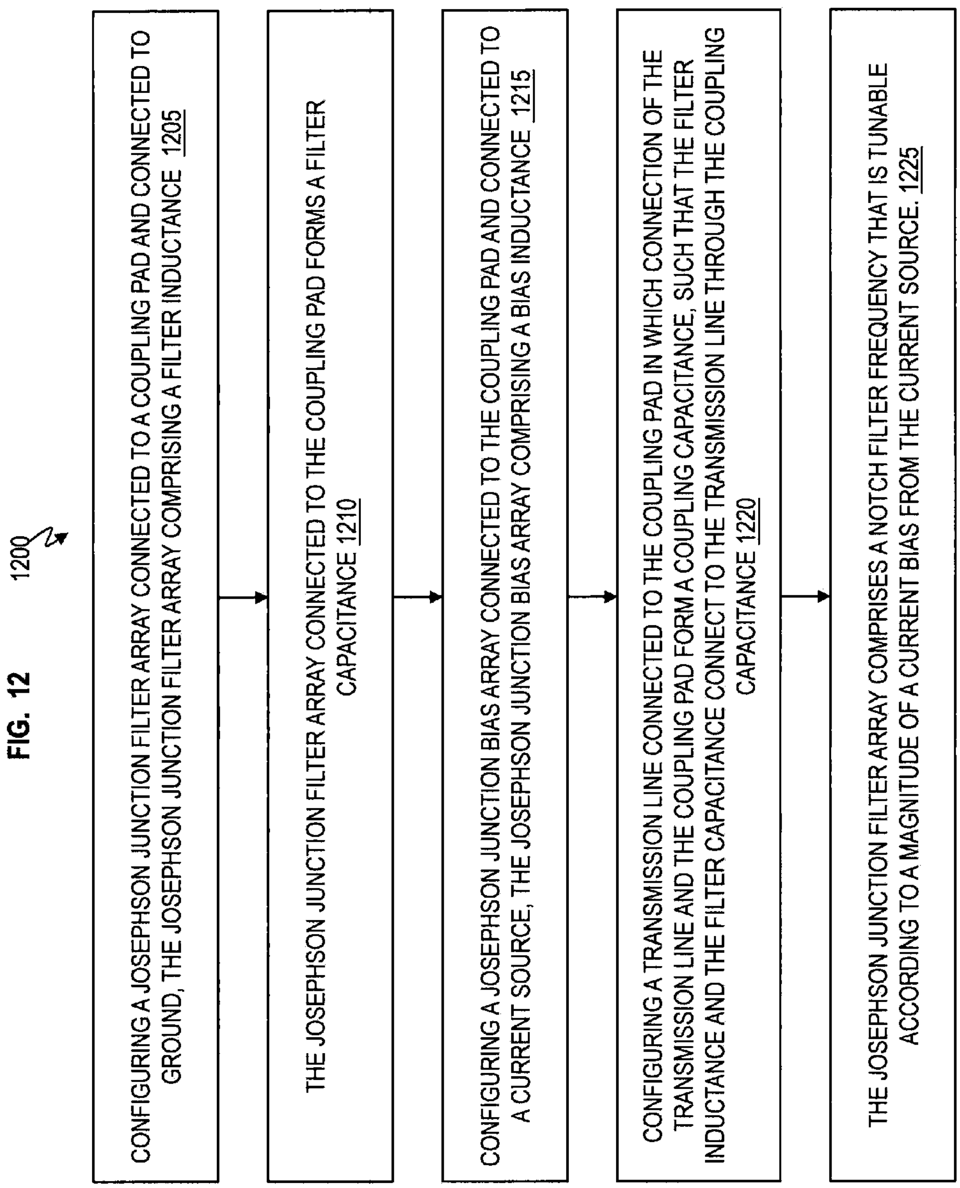
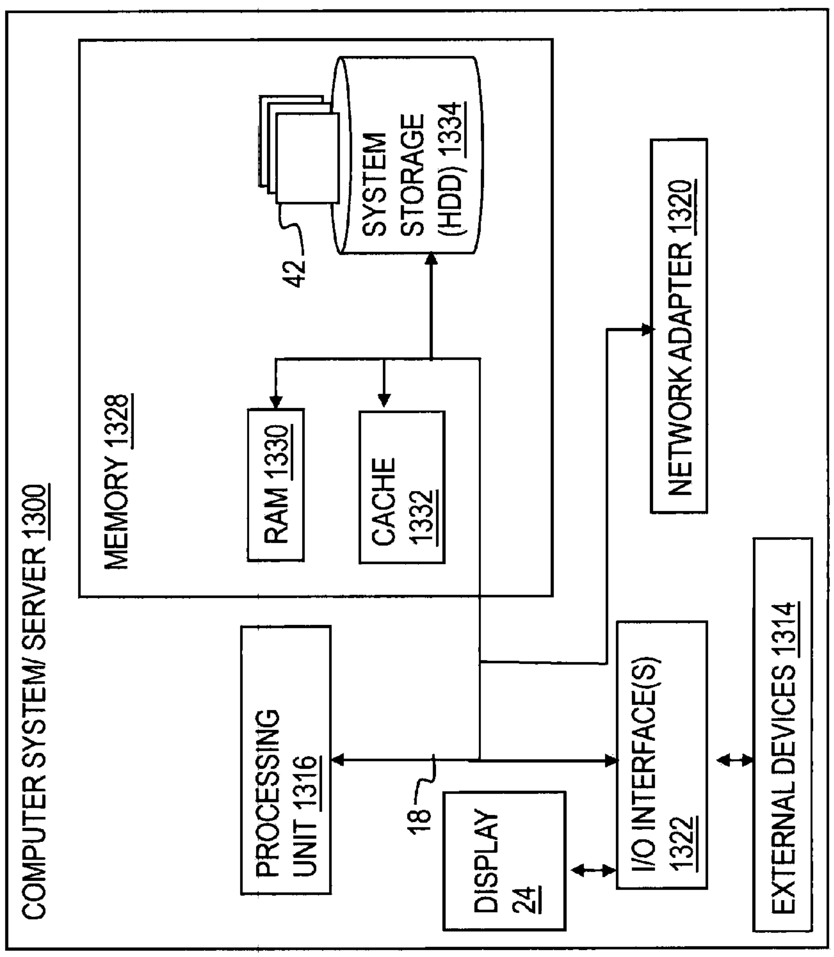

1200
CONFIGURING A JOSEPHSON JUNCTION FILTER ARRAY CONNECTED TO A COUPLING PAD AND CONNECTED TO GROUND, THE JOSEPHSON JUNCTION FILTER ARRAY COMPRISING A FILTER INDUCTANCE 1205
THE JOSEPHSON JUNCTION FILTER ARRAY CONNECTED TO THE COUPLING PAD FORMS A FILTER CAPACITANCE 1210
CONFIGURING A JOSEPHSON JUNCTION BIAS ARRAY CONNECTED TO THE COUPLING PAD AND CONNECTED TO A CURRENT SOURCE, THE JOSEPHSON JUNCTION BIAS ARRAY COMPRISING A BIAS INDUCTANCE 1215
CONFIGURING A TRANSMISSION LINE CONNECTED TO THE COUPLING PAD IN WHICH CONNECTION OF THE TRANSMISSION LINE AND THE COUPLING PAD FORM A COUPLING CAPACITANCE, SUCH THAT THE FILTER INDUCTANCE AND THE FILTER CAPACITANCE CONNECT TO THE TRANSMISSION LINE THROUGH THE COUPLING CAPACITANCE 1220
THE JOSEPHSON JUNCTION FILTER ARRAY COMPRISES A NOTCH FILTER FREQUENCY THAT IS TUNABLE ACCORDING TO A MAGNITUDE OF A CURRENT SOURCE. 1225

FIG. 13


COMPUTER SYSTEM/ SERVER 1300
MEMORY 1328
RAM 1330
CACHE 1332
SYSTEM STORAGE (HDD) 1334
42
PROCESSING UNIT 1316
18
DISPLAY 24
I/O INTERFACE(S) 1322
NETWORK ADAPTER 1320
EXTERNAL DEVICES 1314

TUNABLE SUPERCONDUCTING NOTCH FILTER

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under W911NF-10-1-0324 awarded by Army Research Office (ARO). The Government has certain rights to this invention.

BACKGROUND

The present invention relates to superconducting quantum circuits, and more specifically, to a superconducting tunable notch filter connected to a superconducting quantum circuit.

Superconducting quantum computing is a promising implementation of quantum information technology that involves nano fabricated superconducting circuits, using Josephson junctions as non-linear elements.

For an integrated circuit to behave quantum mechanically, the first requirement is the absence (or reduction) of dissipation. More specifically, all metallic parts need to be made out of a material that has zero resistance at the qubit operating temperature and at the qubit transition frequency. This is essential in order for electronic signals to be carried from one part of the chip to another without energy loss which is a condition for the preservation of quantum coherence. Low temperature superconducting materials are utilized for this task, and accordingly quantum integrated circuit implementations are referred to as superconducting qubits.

SUMMARY

According to one embodiment, a superconductor tunable notch filter is provided. A Josephson junction filter array is connected to a coupling pad and connected to ground, and the Josephson junction filter array comprises a filter inductance. The Josephson junction filter array connected to the coupling pad forms a filter capacitance. A Josephson junction bias array is connected to the coupling pad and connected to a current source, and the Josephson junction bias array comprises a bias inductance. A transmission line is connected to the coupling pad in which connection of the transmission line and the coupling pad forms a coupling capacitance, such that the filter inductance and the filter capacitance connect to the transmission line through the coupling capacitance. The Josephson junction filter array comprises a notch filter frequency that is tunable according to a magnitude of a current bias from the current source.

According to one embodiment, a method for providing a superconductor tunable notch filter. The method includes configuring a Josephson junction filter array connected to a coupling pad and connected to ground. The Josephson junction filter array comprises a filter inductance (L_f). The Josephson junction filter array connected to the coupling pad forms a filter capacitance (C_f). The method includes configuring a Josephson junction bias array connected to the coupling pad and connected to a current source, where the Josephson junction bias array comprises a bias inductance (L_{bias}), and configuring a transmission line connected to the coupling pad in which connection of the transmission line and the coupling pad form a coupling capacitance, such that the filter inductance and the filter capacitance connect to the transmission line through the coupling capacitance. The Josephson junction filter array comprises a notch filter frequency that is tunable according to a magnitude of a current bias from the current source.

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** illustrates a schematic of a superconducting tunable notch filter connected between a superconducting qubit circuit and a dissipative readout and measurement line according to an embodiment;

FIG. **2**A illustrates a graph of an example transmission response of the notch filter tuned to example frequencies according to an embodiment;

FIG. **2**B illustrates a graph of improved T_1 improvement for the superconducting qubit circuit according to an embodiment;

FIG. **3** illustrates a schematic of an implementation of the superconducting tunable notch filter according to an embodiment;

FIG. **4** illustrates a flow chart of utilizing the superconducting tunable notch filter to increase/improve the coherence time (T_1 time) in the excited state according to an embodiment;

FIG. **5** illustrates a block diagram of utilizing multiple superconducting tunable notch filters with more than a single control and measurement line according to an embodiment;

FIG. **6** illustrates a block diagram of utilizing multiple superconducting tunable notch filters on a single line to protect multiple superconducting qubits according to an embodiment;

FIG. **7** illustrates a block diagram of utilizing superconducting tunable multiple notch filters to extend notch bandwidth according to an embodiment;

FIG. **8** illustrates a block diagram of utilizing multiple superconducting tunable notch filters to extend the tunable range of the notch filters according to an embodiment;

FIG. **9** illustrates a block diagram of utilizing the superconducting tunable notch filter for tunable coupling between superconducting qubits according to an embodiment;

FIG. **10** illustrates a block diagram of utilizing superconducting tunable notch filters for selective coupling between multiple qubits and a single readout resonator according to an embodiment;

FIG. **11** illustrates a block diagram of utilizing superconducting tunable notch filters to route photons through a grid of readout resonators by selectively coupling readout resonators according to an embodiment;

FIG. **12** is a flow chart illustrating a method for providing a superconductor tunable notch filter according to an embodiment; and

FIG. **13** illustrates a schematic of a computer system configured to implement, control, and/or operate elements herein according to an embodiment.

DETAILED DESCRIPTION

Embodiments provide a superconducting tunable notch filter. Benefits of the notch filter presented herein, over typical microwave filters, include very low loss due to the use of superconducting materials, while having the ability to tune via the use of Josephson junctions as inductive elements. For example, the inductors made using Josephson junctions have quality factors exceeding 10,000 (Q>10,000). In addition, the notch filter is constructed using the same fabrication techniques as superconducting qubits, so the superconducting notch filter may be implemented on-chip with existing qubit architectures without any modification to standard fabrication procedures, which is advantageous for scaling.

Superconducting qubits which couple to a microwave resonator for readout may lose energy through the resonator, as the resonator is generally strongly coupled to a dissipative environment (which is part of the control and measurement electronics (all of which is referred to as Z environment)). The relaxation time T_1 is limited by the real part of the admittance shunting the qubit at the qubit frequency, in the case of the transmon given by:

$$T_1 = C_\Sigma/(Re[Y(\omega_{ge})]), \qquad \text{Eq. (1)}$$

where C_Σ is the total shunt capacitance across the qubit junction, and $Y(\omega)$ is the total admittance across the qubit junction, and ω_{ge} is the transition frequency of the qubit. The readout resonator acts as a filter between the qubit and dissipative measurement and control environment. When the qubit frequency is close to the readout resonator frequency, coupling of the qubit to the lossy environment is enhanced, reducing the energy relaxation time for the qubit. This enhancement of relaxation rate is known as the Purcell effect.

By detuning the qubit frequency from the readout frequency, relaxation due to the Purcell effect is reduced (the Purcell effect scales as $1/\Delta^2$, where Δ is the qubit-readout detuning). However, coupling between the qubit and readout resonator reduces (scaling as $1/\Delta$) fidelity of the readout. The Purcell effect may also be reduced by increasing the quality factor Q of the readout resonator, but this reduces the speed at which qubit measurements may be taken.

In order to maintain fast and high-fidelity readout while reducing Purcell-enhanced relaxation of the qubit, a notch filter at the qubit frequency may be placed between the readout resonator and dissipative control/measurement transmission lines. Any photons at the qubit frequency which leak out of the readout resonator will, to a large extent, bounce off the notch filter and return to the qubit, rather than dissipate in the control/measurement lines. This is done at no cost to readout fidelity, as photons at the readout frequency pass through the filter unimpeded.

Two state-of-the-art techniques are utilized to reduce the Purcell effect but the state-of-the-art techniques lack the flexibility of the superconducting tunable notch filter presented herein according to embodiments.

For the first state-of-the-art technique, this paper uses quarter-wavelength transmission line stubs to implement a notch filter at the qubit frequency. A transmission line stub is a length of transmission line or waveguide that is connected at one end only, and the free end of the stub is left as an open circuit. In order to gain the maximum benefit from this filter, the qubit frequency must be matched to the filter pole. This matching becomes more critical as other losses to T_1 continue to improve (as the Purcell loss will become the limiting factor to T_1), necessitating a tunable qubit which is prone to reduced coherence times, or fabrication precision which is well beyond present capabilities. The transmission line stubs as implemented in the above reference also result in a fairly broad modification of the external transmission line, while the superconducting tunable filter presented herein (according to embodiments) has a minimal affect outside the filtered frequency.

For the second state-of-the-art technique, another method of filtering uses waveguides to couple between the qubit's readout resonator and the control/measurement electronics. Waveguides are chosen such that the cutoff frequency lies between the qubit and readout frequency, so the qubit is only weakly coupled to Purcell loss through evanescent waves which decay exponentially with waveguide length. The issue with this method is that it requires relatively large and bulky waveguides, and only works in the case where the qubit frequency is below the readout frequency.

Embodiments present a tunable superconducting microwave notch filter. The notch filter consists of a high quality factor lumped-element resonator, capacitively coupled to a microwave transmission line. Insertion of this notch filter is minimally invasive, and does not degrade qubit readout performance. The notch filter inductance is formed by a Josephson junction array, which may be tuned by applying a DC bias current. DC bias is applied through another array of Josephson junctions, which acts as a high impedance at microwave frequencies. The use of superconducting materials allows the filter to have very high rejection at the filter pole, due to low internal dissipation.

Now turning to the figures, FIG. **1** illustrates a circuit schematic **100** of the superconducting tunable notch filter **110**, shown connected between a superconducting transmon qubit circuit **120** and a dissipative readout and measurement line **140** according to an embodiment.

The superconducting tunable notch filter **110** is a tunable two-pole filter, consisting of an LC oscillator capacitively coupled to the microwave transmission line **140**. The LC oscillator is an inductor/Josephson junction filter array **10** and capacitor **15**. The notch filter **110** is inserted between the qubit circuit **120** and control and measurement transmission line **140** of characteristic impedance Z_{env} (Z environment). The Z_{env} **130** represents the impedance of the control/measurement transmission line **140**. The Z_{env} **130** includes control and measurement equipment **180** configured to transmit and measure signals (including microwave signatures) as understood by one skilled in the art. It is understood that the control and measurement equipment has the characteristic impedance of Z_{env} **130**. The transmon qubit circuit **120** includes the transmon qubit **150** and its readout resonator **160**. The transmon qubit **150** includes a Josephson junction device **20** connected in parallel with a capacitor **25**. The readout resonator **160** includes an inductor/Josephson junction device **30** and capacitor **35** connected in parallel (or a CPW (coplanar waveguide) or cps (coplanar stripline) resonator. A capacitor **55** is connected between the readout resonator **160** and the qubit **150**. Note that although the superconducting qubit circuit **120** is described as transmon qubit circuit for explanation purposes, it is understood that the superconducting qubit circuit **120** is not meant to be limited and applies to super conducting qubits circuits that are not transmon circuits.

The notch filter **110** should be placed close to the superconducting qubit circuit **120** such as, e.g., within a wavelength of the qubit frequency. As an example, for a qubit frequency of 5 GHz on silicon or sapphire, the wavelength is about c/5 GHz/sqrt(11) which is approximately (~) 1.8 cm. Accordingly, the notch filter **110** should only be a few millimeters away. The filter inductance L_f of inductor/Josephson junction filter array **10** and capacitance C_f of capacitor **15** are capacitively coupled (via capacitor C_c **165**) to the microwave transmission line **140** via capacitance C_c**165**.

The inductance L_f of the notch filter **110** is formed by an array of Josephson junctions **10** (connected in series). The nonlinearity of the Josephson junctions with respect to current allows for the filter inductance L_f of the Josephson junction filter array **10** to be tuned with the application of a bias current I_{bias}, thereby tuning the poles of the notch filter **110**. The filter inductance L_f of the Josephson junction filter array **10** is given by:

$$L_f(I) = \frac{N\phi_0 / I_C}{\sqrt{1-(I/I_C)^2}}, \qquad \text{Eq. (2)}$$

where I is the bias current (I_{bias}), N is the number of junctions in the array **10**, ϕ_0=h/(2e) is the reduced flux quantum, and I_C is the critical current of the junctions.

In order to apply the current bias (I_{bias}) to the array **10**, a high impedance current source **45** is required. To ensure the current source **45** is high impedance at microwave frequencies (i.e., frequencies in the microwave range in the electromagnetic spectrum), a Josephson junction bias array **40**, of higher inductance L_{bias}, is used.

An additional weakly coupled drive port (drive line) is added to the transmon qubit circuit **120** in order to bypass the notch filter **110** and allow the transmon qubit circuit **120** to be controlled. The drive line coupling capacitance C_d (via capacitor **65**) is chosen to be small enough that the capacitance C_d is not the limiting factor to T_1, and merely requires that a voltage signal can be delivered to the qubit circuit **120** to drive quantum gates.

Example filter response and T_1 improvement are respectively illustrated in FIGS. **2**A and **2**B. According to embodiments, FIG. **2**A illustrates a graph **200** of an example transmission response of the notch filter **110** tuned to notch filter frequency 4.88 GHz (waveform **205**A), tuned to notch filter frequency 4.95 GHz (waveform **210**A), and tuned to notch filter frequency 5 GHz (waveform **215**A). As can be seen, the tunable notch filter **110** blocks frequencies at each particular notch filter frequency it is tuned to. Note that the notch filter **110** is measured by itself (via control and measurement equipment **180**) and not with the qubit circuit **120**.

The notch filter **110** can be tuned down to a lower notch filter frequency by applying a DC bias current (I_{bias}) to the notch filter **110**. As shown by waveform **215**A, the notch filter **110** may be configured to have a natural band stop (block frequencies) at 5 GHz, such as when no I_{bias} current is applied by the current source **45**. Assuming that he qubit frequency of the qubit **150** is at 5 GHz, the qubit frequency (e.g., at 5 GHz) is reflected back to the qubit **150** when the notch filter **110** is tuned to notch filter frequency 5 GHz (naturally in this case without requiring a DC bias). This reflection at the qubit frequency improves the T_1 relaxation time, where the T_1 time measures how long the qubit **150** remains in the excited state. The notch filter **110** reflects the signal back to the qubit **150** at its qubit frequency and reduces the Purcell effect such that the qubit **150** remains in the excited state for a longer length of time before losing energy and moving to the ground state.

As shown by waveform **210**A, the notch filter **110** can be tuned down to notch filter frequency 4.95 GHz (i.e., block frequencies at 4.95 GHz from the transmon qubit circuit **120**) by applying a biasing current (I_{bias}) of 0.2 value is 0.2*I_C, where I_C is the critical current of the junctions in array L_f (labeled **10**). Similarly, when the qubit frequency of the qubit **150** is at 4.95 GHz, the qubit frequency (e.g., at 4.95 GHz) is reflected back to the qubit **150** when the notch filter **110** is tuned down to notch filter frequency 4.95 GHz by applying the DC bias current (I_{bias}) via the current source **45**.

As shown by waveform **205**A, the notch filter **110** can be tuned down to notch filter frequency 4.88 GHz (i.e., block frequencies at 4.88 GHz from the transmon qubit circuit **120**) by applying a biasing current (I_{bias}) of 0.3*I_C. Similarly, when the qubit frequency of the qubit **150** is at 4.88 GHZ, the qubit frequency (e.g., at 4.88 GHz) is reflected back to the qubit **150** when the notch filter **110** is tuned down to notch filter frequency 4.88 GHz by applying the DC bias current (I_{bias}) via the current source **45**.

Referring to FIGS. **2**A and **2**B, for evaluating the transmission response of the transmon qubit circuit **120** connected to the notch filter **110** in circuit **100**, the notch filter **110** has a C_c=13.946 fF (femtofarad) for capacitor **165**, C_f=35.914 fF for capacitor **15**, L_f=21.42 nH (nanohenry) for inductor/Josephson junction filter array **10**, and L_{bias}=200 nH for inductor/Josephson junction bias array **40**. The characteristic impedance of the Z environment (for Z_{env} **130**) is 50 Ω (ohms) as understood by one skilled in the art. It is understood that the control and measurement equipment **180** is part of the Z environment.

According to an embodiment, FIG. **2**B illustrates a graph **250** of T_1 improvement (i.e., spike) when reading out the transmon qubit circuit **120** (particularly the qubit **150**) by the Z environment (Z_{env} **130**). Note that in FIG. **2**B the control and measurement equipment **180** reads (measures) the signals. This particular plot in graph **250** demonstrates improved T**1** for a transmon qubit, and it is understood that other qubits (e.g., that are not transmon) would have a similar improvement. FIG. **2**B shows the graph **250**, bound on T_1 time due to the Purcell effect, with improvement at 5 GHz (waveform **215**B), improvement at 4.95 GHz (waveform **210**B), and improvement at 4.88 GHz (waveform **205**A) according to the matching the notch filter frequency of the notch filter **110** to the particular qubit frequency. It may be assumed that transmon qubit circuit **120** has a qubit capacitance of 60 fF for capacitor **25**, and the qubit **150** is coupled to a 6 GHz quarter wavelength resonator (which means the readout frequency of the readout resonator **160** is 6 GHz. The Z_{env} **130** has a 50Ω characteristic impedance via a **10** fF coupling capacitor **60**. In this model, a 20 mm segment of transmission line (with phase velocity 1.1×108 m/s) is placed between the transmon qubit **120** and the notch filter **110**. As can be seen at each tuned notch filter frequency (5 GHz, 4.95 GHz, 4.88 GHz) of the notch filter **110**, more than an order of magnitude in T_1 improvement exists where the filter is tuned. That is, the energy at each notch filter frequency of the notch filter **110** increases at the example qubit frequency of the transmon qubit **120**, because for each example case, the energy is reflected back to the transmon qubit **120** at the particular qubit frequency allowing the transmon qubit circuit **120** to stay in the excited state for a longer period of time. It is assumed that the qubit frequency is 5 GHz in one case, 4.95 GHz in one case, and 4.88 GHz in another case, and the notch filter frequency of notch filter **110** is respectively tuned to block and reflect each qubit frequency (for each case 5 GHz, 4.95 GHz, 4.88 GHz) back to the transmon qubit **120**. This reflection/block by the notch filter **110** provides T_1 time improvement at the qubit frequency.

As understood by one skilled in the art, it may be difficult to manufacture the qubit **150** with an exact qubit frequency, and the qubit frequency may be within a predefined tolerance. Embodiments are designed such that the maximum qubit frequency of the qubit **150** in the transmon qubit **120** is below the natural frequency blocked (band stop) by the notch filter **110** when no DC bias current (I_{bias}) is applied by the current source **45**. The superconducting notch filter **110** is tuned by applying the DC bias current (I_{bias}) as discussed herein. The notch filter **110** is at its highest (blocking) notch filter frequency when no DC bias current is applied. The tuning of the blocking notch filter frequency of the notch filter **110** may range from being tuned between a few megahertz (e.g., 1, 2, 3, 4, 5 MHz . . . etc.) to maybe ten megahertz (10 MHz).

Now turning to FIG. **3**, there is shown a schematic of a physical implementation of the superconducting tunable notch filter **110** according to an embodiment. More specifically, FIG. **3** is a computer aided design (CAD) drawing of the superconductor tunable notch filter for e-beam lithography. Note that the transmon qubit **120** and the line **140** (including Z_{env} **130**) are not shown, although transmon qubit circuit **120** and the line **140** are understood to be operatively connected to the notch filter **110** as shown in FIG. **1**.

The transmission line **170** is implemented as a coplanar waveguide (CPW) **170**, to which a metallic pad (coupling pad **310**) is capacitively coupled to as capacitance C_c (shown as capacitor **165** in FIG. **1**). Note that the capacitor **165** represents the capacitance (connection) between the coupling pad **310** and the coplanar waveguide **170**. The capacitance of this coupling pad **310** to ground **320** forms the filter capacitance C_f (shown as capacitor **15** in FIG. **1**). As represented by Josephson junction filter array/inductor **10**, an array aluminum-aluminum oxide-aluminum Josephson junctions between the coupling pad **310** and ground **320** form inductance L_f (of Josephson junction filter array **10**). A longer array of Josephson junctions also connecting to the coupling pad **310** forms inductance L_{bias} (shown as Josephson junction bias array/inductor **40** in FIG. **1**). The long array of Josephson junctions **40** has more Josephson junctions than the array of Josephson junctions **10**. The Josephson junction bias array **40** may also be referred to as the DC bias array. A DC bias line **315** connects to the other end of the Josephson junction array **40** to provide the I_{bias} current that tunes the notch filter **110**.

The entire superconducting tunable notch filter **110** is made of superconducting materials. The Josephson junction filter array **10** and the Josephson junction bias array **40** are made of aluminum and aluminum oxide. The array of Josephson junctions in both arrays **10** and **40** are connected in series. One skilled in the art understands how to construct a Josephson junction array. The coupling pad **310**, the CPW/line **170**, DC bias line **315** (connected to the current source **45**), and the ground plane **320** may be made of titanium nitride, niobium, and/or aluminum, etc.

An example mode of operation is now discussed for the circuit **100** according to an embodiment. The first operation when a new qubit circuit **120** and notch filter **110** are being measured is to locate the readout resonator frequency (of the readout resonator **160**) with a control and network equipment **180**.

The readout resonator **160** is a resonator used to infer the state of the qubit **150**; inferring the state of the qubit **150** means determining if the qubit **150** is in the excited state or ground state. When the readout resonator frequency is known (i.e., measured by the control and network equipment **180**), the readout resonator frequency of the readout resonator **160** can be used to find the qubit frequency of the qubit **150** by having a network probe device **185** sweep an auxiliary RF signal in frequency via the drive line. When the auxiliary RF signal matches the qubit frequency of the qubit **150** (as measured and determined by the control and network equipment **180**, the qubit **150** then transitions to the excited state (i.e., the qubit is energized).

Next, the notch filter frequency of the tunable notch filter **110**, with no bias current (I_{bias}) applied, is found with the control and network equipment **180**. A bias current (I_{bias}) is then applied via the current source **45** and increased in magnitude until the notch filter frequency of the notch filter **110** matches the qubit frequency of the qubit **150** in the transmon qubit circuit **120**. The bias current (I_{bias}) can further decrease the notch filter frequency, by further increasing the magnitude of the bias current. To verify that the notch filter **110** is operating as desired, the T_1 time of the qubit **150** is measured (via the control and measurement equipment **180**) with the notch filter **110** tuned on resonance with the qubit **150** (i.e., the notch filter frequency matches the qubit frequency and thus blocks/reflects the qubit frequency from escaping to the Z_{env} **130**) and then turned off resonance with the qubit **150** (i.e., the notch filter frequency does not match the qubit frequency, thus allowing energy at the qubit frequency to dissipate in the Z_{env} **130**). The control and measurement equipment **180** may include a data acquisition card. The data acquisition card analyzes time segments of the phase after excitation, and readout pulses are applied to the device. The T_1 time measures how long, on average, the qubit **150** is able to remain in the excited state before the qubit **150** loses energy and drops to the ground state. When the notch filter **110** is properly tuned on resonance with the qubit **150** (as discussed herein), the T_1 time is at a maximum. The notch filter **110** does not affect the performance of the readout of the readout resonator **160**.

FIG. **4** illustrates a flow chart **400** of utilizing the tunable notch filter **110** to increase the time (i.e., improve T_1 time) in the excited state according to an embodiment.

At block **405**, the control and network equipment **180** is utilized to locate the readout resonator frequency (of the readout resonator **160**) with single-tone spectroscopy. For example, a microwave signal is sent from Z_{env} (by the control and network equipment **180**) to the device under test (i.e., the readout resonator **160** in the transmon qubit circuit **120**). The phase of the reflected signal (i.e., reflected back to the control and network equipment **180**) is monitored while the frequency is swept. As the frequency is swept across the readout resonator **160**, a 360° (degree) phase shift will occur, denoting the location in frequency of the readout resonator **160**. Note that a radio frequency sweep, frequency sweep, or RF sweep refers to scanning a radio frequency band for detecting signals being transmitted thereon. This is implemented using a radio receiver having a tunable receiving frequency. As the frequency of the receiver is changed to scan (sweep) a desired frequency band, a display indicates the power of the signals received at each frequency.

At block **410**, the control and measurement equipment **180** is configured to locate the qubit frequency of the qubit **150**, using two-tone spectroscopy with the readout resonator frequency (of the readout resonator **160**) found in block **405**.

For example, a probe pulse (generated by the probe device **185**, which includes a signal generator to generate pulses) is sent to the qubit drive port/drive line. As the frequency of the probe pulse is swept (i.e., generated across a band of frequencies) by the probe pulse device **185**, the phase of a microwave signal reflected off the readout resonator **160** is monitored and measured at Z_{env} **130** by the control and measurement equipment **180**. In one case, this is measured by down converting the reflected signal via a data acquisition card. When the probe pulse frequency (sent by the probe pulse device **185**) matches the qubit frequency of the qubit **150**, the qubit **150** transitions to the excited state. This results in the readout pulse (of the readout resonator **160**) reflecting (to the control and network equipment **180**) with a shifted phase, indicating that the qubit **150** has been excited.

At block **415**, the control and network equipment **180** is utilized to locate the zero-bias frequency (i.e., no DC bias current (I_{bias}) applied) of the notch filter **110** with single-tone spectroscopy. The same measurement as performed in block **405** (for the resonator frequency) is executed, but this time the frequency is swept (via the control and network equipment **180**) around the frequency region/band that the notch filter **110** is expected to be located. For example, a microwave signal is sent from Z_{env} (by the control and network equipment **180**) to the device under test (i.e., the notch filter **110**). The phase of the reflected signal (i.e., reflected back to the control and network equipment **180**) is monitored while the frequency is swept. As the frequency is swept across the expected frequencies, a 360° (degree) phase shift will occur (as measured by the control and network equipment **180**), denoting the notch filter frequency of the notch filter **110**.

Once the notch filter frequency of the notch filter **110** is determined (with no DC bias current applied), the DC bias current (I_{bias}) in the notch filter **110** is (incrementally) increased until the notch filter frequency drops down to match the qubit frequency of the superconducting qubit **150** at block **420**. For example, a DC bias current (by the current source **45**) is applied to the notch filter **110**, and its change in notch filter frequency is measured at a particular bias point by repeating the measurement of block **415** (noting that the highest possible frequency was found in block **415** with zero bias current).

At block **425**, the control and network equipment **180** is utilized to characterize qubit T_1 time with the notch filter frequency of the notch filter **110** tuned on resonance with the qubit frequency and off resonance with the qubit frequency to evaluate performance of the notch filter **110**. A sweep of T_1 versus current bias (I_{bias}) may be used to finely optimize bias current, such that the T_1 time is at a maximum (before the qubit **150** loses energy). For example, a measurement of the qubit's energy relaxation time (T**1**) is performed with bias current applied (via control and network equipment **180**) until the bias current causes the notch filter frequency to match the qubit frequency. T_1 is measured again with the notch filter detuned (i.e., matching the qubit frequency), allowing the improvement in T_1 to be observed.

Note that T_1 is determined by exciting the qubit **150** (apply a pi (π) pulse at the qubit frequency on the drive port by the probe device **185**), waiting a period of time, then applying a pulse at the readout frequency (via the control and network equipment **180**), and measuring the phase of the reflected signal (at Z_{env} **130** by the control and measurement equipment **180** (e.g., via the data acquisition card). After many repeated measurements at several different wait times (e.g., increasing intervals of wait times), an exponentially decaying trend is observed for probability of the qubit **150** being in the excited state versus time elapsed since the qubit was prepared in the excited state (application of π pulse by the probe device **185**). The decay constant of this exponential decay is T_1.

The control and network equipment **180**, the probe device **185**, and/or the current source **45** may be implemented in and/or controlled by a computer **1300** in FIG. **13**. Therefore, the computer **1300** may be configured to send a pulse to place the qubit **150** into the excited state. The computer **1300** may be configured to tune the notch filter frequency on resonance as the qubit frequency, by increasing and decreasing the magnitude of the current bias (I_{bias}). Further details of the computer **1300** are discussed herein.

FIGS. **5** through **11** illustrate various examples of using the tunable notch filter **110** according to embodiments. Some details of the transmon qubit **120**, line **140**, and superconducting tunable notch filter **110** in FIGS. **1** and **3** may be omitted but are understood to be present. Also, reference can be made to FIGS. **1-4** and **13**.

FIG. **5** illustrates a block diagram of utilizing multiple tunable notch filters **110** with more than a single control and measurement line according to an embodiment. This allows the use of multiple Z environments (Z_{env} **130**) each with its own respective notch filter **110**. Each Z environment is connected to its own transmission and measurement line.

FIG. **6** illustrates a block diagram of utilizing multiple notch filters **110** on a single line to protect multiple transmon qubits **120** according to an embodiment. In this case, each transmon qubit **120** has its own respective notch filter **110** in a one-to-one relationship, such that a first notch filter **110** has its notch filter frequency tuned to the qubit frequency of a first transmon qubit **120** (i.e., the qubit **150**), a second notch filter **110** has it notch filter frequency tuned to the qubit frequency of the second transmon qubit **120**, through a last notch filter **110** that has its notch filter frequency tuned to the qubit frequency of the last transmon qubit **120**.

FIG. **7** illustrates a block diagram of utilizing multiple notch filters to extend notch bandwidth according to an embodiment. In this case, a first through a last notch filter **110** is added between the transmon qubit **120** and the Z_{env} **130**. Each of the notch filters **110** may be tuned to nearly the same notch filter frequency to increase the bandwidth of the notch filters **110** as a whole. The increased bandwidth provides multiple sharp resonances which are placed next to each other to form one broad feature. Accordingly, tuning the multiple notch filters **110** to nearly the same notch filter frequency results in a multi-pole filter.

FIG. **8** illustrates a block diagram of utilizing multiple notch filters **110** to extend the tunable range of the notch filters **110** according to an embodiment. The tunable range of an individual notch filter **110** is the range/spectrum in which the notch filter frequency can be moved (adjusted) down from its highest notch filter frequency to its lowest notch filter frequency. In FIG. **8**, the first notch filter **110** may have a tunable notch filter frequency range from 5.000 to 5.005, the second notch filter **110** may have a tunable notch filter frequency range from 5.004 to 5.009, the third notch filter **110** may have a tunable notch filter frequency range from 5.008 to 5.013 GHz, the fourth notch filter **110** may have a tunable notch filter frequency range of 5.012 to 5.017 GHz, and so forth. Each of the first through the last notch filters **110** may be constructed to have a slightly different tunable notch filter frequency range (e.g., with a small overlap). In FIG. **8**, only one notch filter **110** may be utilized at a given time to reflect the qubit frequency back to the transmon qubit **120** (particularly back to the qubit **150**).

FIG. **9** illustrates a block diagram of utilizing the notch filter **110** for tunable coupling between transmon qubits **120** according to an embodiment. The notch filter **110** is positioned between a first transmon qubit **120** and a second transmon qubit **120**, where the first and second transmon qubits **120** are at the same qubit frequency. When the notch filter **110** is off resonance, which means that the notch filter frequency is not tuned to the qubit frequency of the first and second transmon qubits **120**, the first transmon qubit **120** can couple to the second transmon qubit **120** (and vice versa). When the notch filter frequency of the notch filter **110** is on resonance, which means that the notch filter frequency is tuned to the qubit frequency of the first and second transmon qubits **120**, the first transmon qubit **120** cannot couple with the second transmon qubit **120** (and vice versa). The coupling strength can be varied from strong to weak.

FIG. **10** illustrates a block diagram of utilizing notch filters for selective coupling between multiple qubits **150** and a single readout resonator **160** according to an embodiment. FIG. **10** has first through last qubits **150** corresponding to first through last notch filters **110** on a one-to-one basis. For one of the first through last qubits **150** to couple to the single readout resonator **160**, the respective notch filter **110** (between the readout resonator **160**) has to be tuned off resonance. For example, for the first qubit **150** to couple with the readout resonator **160**, the first notch filter **110** has to have its notch filter frequency tuned off resonance with the qubit frequency of the first qubit **150**. The same process is required for each of the qubits **150** to couple with the single readout resonator **160**.

FIG. **11** illustrates a block diagram of utilizing notch filters to route photons through a grid of readout resonators by selectively coupling readout resonators according to an embodiment. FIG. **11** has a first through last readout resonator **160** and a first through last notch filter **110**. In the grid of readout resonators **160**, each readout resonator **160** has one notch filter **110** connected in between another readout resonator **160**. Having the notch filter **110** connected in between any two readout resonators **160** allows the notch filter **110** connected in between to selective couple the two readout resonators **160** together and/or block the two readout resonators **160** from being coupled together. Having every two (nearby) readout resonators **160** connected by a notch filter **110** allows the notch filter **110** to shuffle a photon throughout the grid by switching from off resonance to on resonance. Assume that the readout frequency is the same for each of the first through last readout resonators **160** and the first through last notch filters **110** can each tune the readout frequency by applying a DC bias current (I_{bias}). Assume that the control and measurement equipment **180** (e.g., a signal source) at Z_{env} **130** sends a signal to the first readout resonator **160** in order to excite a photon (and/or a quantum of light or energy) in the first readout resonator **160** (when the last notch filter **110** is off resonance), and the last notch filter **110** blocks the photon from being reflected back to the Z_{env} **130** by being tuned to on resonance with the readout frequency of the first readout resonator **160**. Assume that all first through last notch filters **110** remain on resonance (i.e., are not tuned to the readout frequency) until tuned to on resonance (e.g., by the computer **1300** causing the I_{bias} to be applied). To selectively couple the first readout resonator **160** to the second readout resonator **160**, the first notch filter **110** is tuned off resonance which allows the photon to travel from the first readout resonator **160** to the second readout resonator **160**, and then the first notch filter **110** is again tuned on resonance with the readout frequency. Note that in FIG. **11** the first through last notch filters **110** act like switches that can be opened (e.g., off resonance) to allow the photon to travel and closed (e.g., on resonance) to trap the photon at a particular readout resonator **160**. Now continuing the example, the second notch filter **110** can be opened (by tuning off resonance) in order to allow the photon to travel from the second readout resonator **160** to the third readout resonator **160**, and then the second notch filter **110** can be closed thus trapping the photon at the third readout resonator **160**. Optionally, the seventh notch filter **110** could have been opened to allow the photon to travel from the second readout resonator **160** to the fifth readout resonator **160**.

Assuming that the photon is at the third readout resonator **160** in FIG. **11**, the third notch filter **110** can be opened to allow the photon to travel from the third readout resonator **160** to the fourth readout resonator **160**, and the third notch filter **110** is closed to trap the photon at the fourth readout resonator **160**. This process of opening and closing the notch filter coupling two readout resonators can continue until the photon is back at the first readout resonator **160**. At which case, the last notch filter **110** can be opened (i.e., tuned off resonance) to allow the photon to travel to the Z_{env} **130**.

Now referring to FIG. **12**, FIG. **12** is a flow chart **1200** illustrating a method for providing a superconductor tunable notch filter according to an embodiment. Reference can be made to FIGS. **1-11** and **13**.

At block **1205**, the Josephson junction filter array **10** is connected to a coupling pad **310** and connected to ground, and the Josephson junction filter array **10** comprises a filter inductance L_f. The coupling pad **310** is electrically connected to the CPW/line **170** in order to connect to, e.g., the transmon qubit **120** and Z_{env} **130** (on line **140**).

At block **1210**, the Josephson junction filter array **10** connected to the coupling pad **310** forms a filter capacitance C_f. At block **1215**, the Josephson junction bias array **40** is connected to the coupling pad **310** and connected to the current source **45**, and the Josephson junction bias array **40** comprises the bias inductance L_{bias}.

At block **1220**, the transmission line **170** is connected to the coupling pad **310** in which the connection of the transmission line **170** and the coupling pad **310** form the coupling capacitance C_c, such that the filter inductance L_f and the filter capacitance C_f connect to the transmission line **170** through the coupling capacitance C_c.

At block **1225**, the Josephson junction filter array **10** comprises a notch filter frequency that is tunable according to a magnitude of the DC current bias (I_{bias}) from the current source **45**.

The notch filter frequency at zero bias current is designed based on values for the filter inductance L_f, the filter capacitance C_f, the bias inductance L_{bias}, and the coupling capacitance C_c. The notch filter frequency at zero bias current is roughly given by $f=1/(2\pi \mathrm{sqrt}(L_f \cdot (C_f+C_c)))$.

The notch filter **110** is designed such that increasing the magnitude of the current bias (I_{bias}) decreases the notch filter frequency, thus allowing the notch filter **110** to be tuned. The notch filter **110** is configured such that the notch filter frequency has different tuning ranges according to the values selected for the filter inductance L_f, the filter capacitance C_f, the bias inductance L_{bias}, and the coupling capacitance C_c. The tuning range (of the notch filter **110**) is a range of frequencies in which the notch filter frequency can vary by changing the current bias. For example, if the zero bias current notch filter frequency is 6 GHz and the notch filter frequency can be tuned down to 5.5 GHz, then the tuning range is from 5.5 to 6.0 GHz (which is a span of 500 MHz).

The notch filter **110** is connected between the transmon qubit circuit **120** and the transmission Z environment (Z_{env} **130** on transmission and measurement line **140**). The transmon qubit circuit **120** comprises the qubit **150** and the readout resonator **160**. The transmission environment (on transmission line **140**) comprises an environment impedance (encompassed by Z_{env} **130**) which is typically 50 ohms. The environment impedance, represented by Zenv **130**, takes into account the impedance of the control and measurement equipment **180**. The notch filter **110** affects the qubit frequency only and does not affect readout of the readout resonator **160**.

The notch filter frequency of the notch filter **110** is tuned to a qubit frequency of the transmon qubit circuit **120** (particularly qubit **150**) by increasing the magnitude of the current bias until the notch filter frequency matches the qubit frequency.

A plurality of notch filters **110** are provided (individually) between the transmon qubit circuit **120** and a plurality of transmission Z environments (Z_{env} **130**), where each of the plurality of transmission environments have a different transmission line. Reference can be made to FIG. **5**.

A plurality of notch filters **110** are provided between a plurality of transmon qubit circuits **120** and a (single) transmission Z environment (Z_{env} **130**). Reference can be made to FIG. **6**.

A plurality of notch filters **110** are provided between a transmon qubit circuit **120** and a transmission Z environment, where each of the plurality of notch filters **110** are tuned to a notch filter frequency within a predefined range. Reference can be made to FIG. **7**.

A plurality of notch filters **110** between a transmon qubit circuit **120** and a transmission Z environment, where each of the plurality of notch filters **110** are tuned to a different notch filter frequency. Reference can be made to FIG. **8**.

The notch filter **110** is provided between a first transmon qubit circuit **120** and a second transmon qubit circuit **120**, where the first transmon qubit circuit **120** and the second transmon qubit circuit **120** have a same qubit frequency. Tuning the notch filter frequency of the notch filter **110** to the same qubit frequency (of the first and second transmon qubit circuits **120**) blocks communication between the first transmon and second transmon qubit circuits **120**. Conversely, tuning the notch filter frequency of the notch filter **110** to be different (i.e., off resonance) from the same qubit frequency (of the first and second transmon qubit circuits **120**) allows communication between the first and second transmon qubit circuits **120**. Reference can be made to FIG. **9**.

A plurality of qubits **150** are connected to a (single) readout resonator **160**, where each of the plurality of qubits **150** are connected to the readout resonator **160** by respective notch filters **110** (i.e., one notch filter connected in between each qubit **150** and the readout resonator **160**). One of the plurality of qubits **150** is selectively coupled to the readout resonator **160** by tuning a notch filter frequency of a corresponding one of the respective notch filters **110** off resonance (where the corresponding notch filter is positioned between particular qubit **150** being turned on). Reference can be made to FIG. **10**.

A grid of readout resonators **160** are individually connected to one another by corresponding notch filters **110**. Any two readout resonators **160** are selectively coupled together by tuning a corresponding notch filter **110**, connected in between the any two readout resonators **160**, off resonance. Reference can be made to FIG. **11**.

The notch filter **110** is tuned to a notch filter frequency that matches a qubit frequency of the qubit transmon circuit **120** such that the notch filter frequency (of the notch filter **110**) reflects the (energy/photons at the) qubit frequency back to the qubit transmon circuit **120**. Reflecting the qubit frequency back (i.e., reflecting the energy/photons at the qubit frequency) to the qubit transmon circuit **120** causes the qubit transmon circuit **120** (particularly the qubit **150**) to remain in an excited state longer than if the qubit frequency is not reflected.

Referring now to FIG. **13**, a schematic of an example computer system/server **1300** (computer) that may implement, connect to, and/or control elements discussed herein. Examples of well-known computing systems, environments, and/or configurations that may be suitable for use with computer system **1300** include, but are not limited to, personal computer systems, server computer systems, thin clients, thick clients, handheld or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputer systems, mainframe computer systems, and distributed cloud computing environments that include any of the above systems or devices, and the like.

Computer system **1300** may be described in the general context of computer system executable instructions, such as program modules, being executed by a computer system. Generally, program modules may include routines, programs, objects, components, logic, data structures, and so on that perform particular tasks or implement particular abstract data types. Computer system/server **1300** may be practiced in distributed cloud computing environments where tasks are performed by remote processing devices that are linked through a communications network. In a distributed cloud computing environment, program modules may be located in both local and remote computer system storage media including memory storage devices.

The components of computer system/server **1300** may include, but are not limited to, one or more processors or processing units **1316**, a system memory **1328**, and a bus **1318** that couples various system components including system memory **1328** to processor **1316**. The processor units **1316** include processing circuitry to read, process, and execute computer executable instructions as understood by one skilled in the art.

Bus **1318** represents one or more of any of several types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port, and a processor or local bus using any of a variety of bus architectures. By way of example, and not limitation, such architectures include Industry Standard Architecture (ISA) bus, Micro Channel Architecture (MCA) bus, Enhanced ISA (EISA) bus, Video Electronics Standards Association (VESA) local bus, and Peripheral Component Interconnect (PCI) bus.

Computer system/server **1300** typically includes a variety of computer system readable media. Such media may be any available media that is accessible by computer system/server **1300**, and it includes both volatile and non-volatile media, removable and non-removable media. System memory **1328** can include computer system readable media in the form of volatile memory, such as random access memory (RAM) **1330** and/or cache memory **1332**. Computer system/server **1300** may further include other removable/non-removable, volatile/non-volatile computer system storage media. By way of example only, storage system **1334** can be provided for reading from and writing to a non-removable, non-volatile magnetic media (not shown and typically called a "hard drive", "hard disk", and/or "hard disk drive"). Although not shown, a magnetic disk drive for reading from and writing to a removable, non-volatile magnetic disk (e.g., a "floppy disk"), and an optical disk drive for reading from or writing to a removable, non-volatile optical disk such as a CD-ROM, DVD-ROM or other optical media can be provided. In such instances, each can be connected to bus **1318** by one or more data media interfaces. As will be further depicted and described below, memory **1328** may include at least one program product having a set (e.g., at least one) of program modules that are configured to carry out the functions of embodiments of the invention.

The memory **1328** by way of example, and not limitation, may include an operating system, one or more application programs, other program modules, and program data shown as program modules **42**. The operating system, one or more application programs, other program modules, and program data (or some combination thereof) may include an implementation of a networking environment. The program modules **42** (which may be one or more software applications) are configured to carry out the functions and/or methodologies of embodiments as described herein

Computer system/server **1300** may also couple with one or more external devices **1314** such as a keyboard, a pointing device, a display **1324**, etc.; one or more devices that enable a user to interact with computer system/server **1300**; and/or any devices (e.g., network card, modem, etc.) that enable computer system/server **1300** to communicate with one or more other computing devices. Such communication can occur via Input/Output (I/O) interfaces **1322**. Still yet, computer system/server **1300** can communicate with one or more networks such as a local area network (LAN), a general wide area network (WAN), and/or a public network (e.g., the Internet) via network adapter **1320**. As depicted, network adapter **1320** communicates with the other components of computer system/server **1300** via bus **1318**. It should be understood that although not shown, other hardware and/or software components could be used in conjunction with computer system/server **1300**. Examples, include, but are not limited to: microcode, device drivers, redundant processing units, external disk drive arrays, RAID systems, tape drives, and data archival storage systems, etc.

The present invention may be a system, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present invention.

The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), astatic random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

Computer readable program instructions for carrying out operations of the present invention may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Smalltalk, C++ or the like, and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The computer readable program instructions may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In some embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present invention.

Aspects of the present invention are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

What is claimed is:

1. A superconductor tunable notch filter comprising:

a Josephson junction filter array connected to a coupling pad and connected to ground, the Josephson junction filter array comprising a filter inductance;

wherein the Josephson junction filter array connected to the coupling pad forms a filter capacitance;

a Josephson junction bias array connected to the coupling pad and connected to a current source, the Josephson junction bias array comprising a bias inductance; and

a transmission line connected to the coupling pad in which connection of the transmission line and the coupling pad form a coupling capacitance, such that the filter inductance and the filter capacitance connect to the transmission line through the coupling capacitance;

wherein the Josephson junction filter array comprises a notch filter frequency that is tunable according to a magnitude of a current bias from the current source.

2. The filter of claim **1**, wherein the notch filter frequency at zero bias current is designed based on values for the filter inductance, the filter capacitance, the bias inductance, and the coupling capacitance.

3. The filter of claim **1**, wherein the notch filter is designed such that increasing the magnitude of the current bias decreases the notch filter frequency, thus allowing the notch filter to be tuned.

4. The filter of claim **2**, wherein the notch filter is configured such that the notch filter frequency has different tuning ranges according to the values selected for the filter inductance, the filter capacitance, the bias inductance, and the coupling capacitance;

wherein a tuning range is a range of frequencies in which the notch filter frequency can vary by changing the current bias.

5. A method for providing a superconductor tunable notch filter, the method comprising:

configuring a Josephson junction filter array connected to a coupling pad and connected to ground, the Josephson junction filter array comprising a filter inductance (L_f);

wherein the Josephson junction filter array connected to the coupling pad forms a filter capacitance (C_f);

configuring a Josephson junction bias array connected to the coupling pad and connected to a current source, the Josephson junction bias array comprising a bias inductance (L_{bias});

configuring a transmission line connected to the coupling pad in which connection of the transmission line and the coupling pad form a coupling capacitance, such that the filter inductance and the filter capacitance connect to the transmission line through the coupling capacitance;

wherein the Josephson junction filter array comprises a notch filter frequency that is tunable according to a magnitude of a current bias from the current source.

6. The method of claim **5**, wherein the notch filter frequency at zero bias current is designed based on values for the filter inductance, the filter capacitance, the bias inductance, and the coupling capacitance.

7. The method of claim **5**, wherein the notch filter is designed such that increasing the magnitude of the current bias decreases the notch filter frequency, thus allowing the notch filter to be tuned.

8. The method of claim **6**, wherein the notch filter is configured such that the notch filter frequency has different tuning ranges according to the values selected for the filter inductance, the filter capacitance, the bias inductance, and the coupling capacitance;

wherein a tuning range is a range of frequencies in which the notch filter frequency can vary by changing the current bias.

9. The method of claim **5**, further comprising connecting the notch filter between a superconducting qubit circuit and a transmission environment.

10. The method of claim **9**, wherein the superconducting qubit circuit comprises a qubit and a readout resonator;

wherein the readout resonator is coupled to an environmental impedance.

11. The method of claim **9**, furthering comprising tuning the notch filter frequency to a qubit frequency of the superconducting qubit circuit by increasing the magnitude of the current bias until the notch filter frequency matches the qubit frequency;

wherein the notch filter affects the qubit frequency only and does not affect readout of the readout resonator.

12. The method of claim **5**, further comprising providing a plurality of notch filters between a superconducting qubit circuit and a plurality of transmission environments, each of the plurality of transmission environments having a different transmission line.

13. The method of claim **5**, further comprising providing a plurality of notch filters between a plurality of superconducting qubit circuits and a transmission environment.

14. The method of claim **5**, further comprising providing a plurality of notch filters between a superconducting qubit circuit and a transmission environment, wherein each of the plurality of notch filters are tuned to the notch filter frequency within a predefined range.

15. The method of claim **5**, further comprising providing a plurality of notch filters between a superconducting qubit circuit and a transmission environment, wherein each of the plurality of notch filters are tuned to a different notch filter frequency.

16. The method of claim **5**, further comprising providing the notch filter between a first superconducting qubit circuit and a second superconducting qubit circuit, the first superconducting qubit circuit and the second superconducting qubit circuit having the same qubit frequency;

wherein tuning the notch filter frequency of the notch filter to the same qubit frequency blocks communication between the first superconducting qubit circuit and the second superconducting qubit circuit;

wherein tuning the notch filter frequency of the notch filter to be different from the same qubit frequency allows communication between the first superconducting qubit circuit and the second superconducting qubit circuit.

17. The method of claim **5**, further comprising providing a plurality of qubits connected to a readout resonator, each of the plurality of qubits connected to the readout resonator by respective notch filters;

selectively coupling one of the plurality of qubits to the readout resonator by tuning the notch filter frequency of a corresponding one of the respective notch filters off resonance.

18. The method of claim **5**, further comprising providing a grid of readout resonators individually connected to one another by corresponding notch filters;

selectively coupling any two readout resonators together by tuning a corresponding one of the corresponding notch filters, connected in between the any two readout resonators, off resonance.

19. The method of claim **9**, wherein the notch filter is tuned to the notch filter frequency that matches a qubit frequency of the superconducting qubit circuit such that the notch filter reflects the qubit frequency back to the superconducting qubit circuit.

20. The method of claim **19**, wherein reflecting the qubit frequency back to the superconducting qubit circuit causes the superconducting qubit circuit to remain in an excited state longer than if the qubit frequency is not reflected.

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